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TEXACO INCORPORATED

FINAL REPORT

ON

LUNAR DRILL FEASIBILITY STUDY

Performed for
Jet Propulsion Laboratory
Pasadena, California

Based on Work Statement SW-1300
of JPL Contract No. N-33552
(Subcontract under NASA Contract No. NASW-6)

Bellaire, Texas

January 13, 1961

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FEASIBILITY STUDY

I. SUMMARY

A short study has been conducted to determine the feasibility of a device for producing a hole in the lunar surface. The study includes both a literature survey and an experimental program.

The experimental program investigated both rotary and percussive drilling with low thrust and no flushing fluid. Rotary drilling does not appear feasible due to the lack of sufficient thrust for effective cutting. Percussive drilling, on the other hand, appears to be quite acceptable for producing the required hole and is capable of reasonable drilling rates when the cuttings are removed from the hole mechanically.

II. INTRODUCTION

Texaco Inc. has conducted a short term feasibility study in connection with the NASA Lunar program. The study is sponsored by the Jet Propulsion Laboratory, who has the responsibility of executing the initial phases of this program.

The specific purpose of this study was to generate quantitative engineering data needed for technical definition of feasible devices for performing various types of automatic drilling operations from an unmanned spacecraft placed on the moon. Preliminary design of feasible devices was to be considered.

The problem was to determine if a device could be proposed which would not weigh more than 60 lbs. and yet be capable of producing a hole 2 to 5 feet deep in the lunar surface. The maximum static thrust available to drive such a device into the surface is 50-75 lbs. force. The drilling mechanism should produce a hole which allows the "best" sampling possible of those formations penetrated, and it should be of adequate size and character to allow the use of such subsurface logging tools as appear feasible. Power requirements should be very carefully examined. Mechanical reliability is of utmost importance, and should receive high priority in final design considerations.

Three types of information should result from the drilling of a hole in the lunar surface. These are:

1) An estimation of drilling hardness as a function of depth should be obtained from the drilling log, i.e., the record of depth of penetration of the drill as a function of time. This data will provide information on the relative hardness and stratification of the near-surface layers.

2) In the process of producing the hole, samples of the formations should be made available at the surface for chemical and physical analysis.

3) Finally, the hole itself should provide access to the subsurface formations for downhole logging instrumentation to determine as many of the in situ properties of the lunar interior as possible.

In the light of the above, the following specifications may be set forth for the first hole to be drilled into the surface of the moon:

1) Diameter - Assuming that the ultimate purposes of this drilling program are, (a) to provide access to the lunar interior for purposes of making physical measurements or "logging" and (b) to provide a sample of the subsurface material for analysis at the surface of the moon or on earth (coring), it appears necessary to consider a hole diameter greater than 1" (25mm). 1-1/4" will probably be sufficient.

2) Depth - For the initial efforts, depths shall be limited by the available storage space (length) in the space vehicle. For the sake of reliability, no telescoping or collapsible drill stem assemblies will be considered at this time. Evidently a three to six foot drill can be anticipated, allowing total depth of the hole to be between two and five feet below the bottom of the spacecraft storage chamber.

3) Hole Shape and Wall Contamination - Since, for many of the physical measurements being contemplated, intimate contact between the sensing elements and the walls of the hole is required, the hole should be as smooth and regular as possible. Any fluid used to lubricate the bit or remove cuttings from the hole will immediately penetrate and contaminate the formation in the vicinity of the hole, introducing extraneous material which will complicate the problem of data reduction and possibly reduce the value of the results. For this reason the hole should be drilled dry; and, any cleaning should be mechanical (as in the fluted drills used to drill masonry, metal, etc.).

4) Heat Dissipation - One of the most severe

restrictions on the drilling program will be imposed by the dissipation of heat produced during the drilling process. At this time, no quantitative data on heat produced during "dry" drilling is available. This heat production will limit the rate at which hole can be drilled, not only because of the desire to disturb the thermal environment in the formation as little as possible, but because of the mechanical limits of the drill itself.

It is possible that the practical minimum rate of penetration for the drill may be such as to imply a rate of heat production downhole of such magnitude as to render direct downhole equilibrium temperature measurements impossible for a considerable period of time. In the event that this should prove to be the case, the drilling program will be based on the maximum practical rate consistent with the thrust and power available from the spacecraft and downhole time-temperature measurements will have to be extrapolated to equilibrium conditions.

One aspect of any apparatus to be proposed for the lunar exploration program which deserves paramount consideration is its expected reliability. On the basis of Texaco's past experience in field exploration and well surveying, it is felt that a high degree of reliability in field equipment implies that a maximum of mechanical simplicity be employed in its design. This is particularly true for unmanned equipment to be used in a remote location where field repairs and adjustments are somewhat difficult to arrange. This principle of simplicity should apply not only to the design of the apparatus, but to the operational program in which this apparatus is to participate.

In the original work proposal submitted to Jet Propulsion Laboratory, dated July 9, 1960, a discussion was presented of the various possible state of the art methods of producing a hole in the lunar surface (acidizing, burning, sand blasting, shaped charges, etc.). As a result of this discussion, it was concluded that only by both drilling and cleaning the hole by purely mechanical means could physical and chemical contamination of the formation adjacent to the borehole be avoided. Following discussions with Jet Propulsion Laboratory on July 18, 1960, it was decided that the initial experimental program was to consist of an evaluation of dry drilling. No flushing or cooling fluid was to be used.

III. MECHANICAL METHODS FOR PRODUCING HOLE

There are three basic mechanical methods of drilling rock. They may best be classified by the action with which they impart energy to the rock. The three methods are rotary, percussion, and a combination of the first two known as rotary-percussion. Fig. 1 schematically illustrates the action of each method.

Rotary drilling is a method by which a shearing action is imparted to the rock by the rotary motion of the bit. The ability to cut the rock depends on two things. First, the bit must be forced against the rock with sufficient thrust to make the bit "bite in". The bit then needs only enough torque to shear the rock between the adjacent cutting surfaces of the bit.

Percussion drilling depends on high impact energy exchange between the bit and rock. A small portion of the rock is fractured with each impact, and the bit is indexed to a new spot before the next blow.

Rotary-percussion drilling is as its name implies - a combination of both rotary and percussion action. The bit is held in contact with the formation so that after each percussive blow the rotary motion of the bit will shear off the rock between the indentations, thereby giving larger cuttings and consequently more efficient drilling.

Penetration rate versus applied thrust for various methods of mechanical drilling are plotted in Fig. 2.

The extreme simplicity of the machinery required to produce a hole by the rotary method is a feature which is highly desirable for the lunar drill, therefore, rotary drilling deserves serious consideration. However, since the lunar drill is quite limited in thrust there was some question as to whether or not this method might be effectively employed. In order to evaluate rotary drilling with low thrust (50-75 lbs.) a drill press was converted in such a way as to allow the bit thrust and RPM to be varied and to measure power input and rate of penetration. The results of these tests, shown in Table I, are somewhat discouraging. It is possible to drill the required diameter hole only in a very soft rock. Hard rock can be penetrated with only small diameter bits (1/4" or less). The limiting factor is thrust. With all bits tested there appears to be a threshold force required to make the bit "bite in" for effective cutting. In hard rock this required force simply exceeds that which is available. When insufficient force is available the bit merely scrapes the surface of the rock with a grinding action resulting in the generation of excessive heat accompanied by excessive bit wear. It therefore appears feasible to consider the rotary method only if there is additional strong evidence of a very soft formation or heavy dust layers.

Percussive drilling requires somewhat more complex machinery, but published data indicate that holes of the proper size may be drilled in the hard rocks such as granite with light thrust and reasonable power consumption. For instance, one manufacturer indicates that penetration rates of 40"/min. in very hard sandstones are possible with the expenditure of the equivalent of 2,760 watts. Since this power level would be difficult to accommodate in the spacecraft, we will probably want to operate at a somewhat lower level. In order to get the same efficiency of penetration a low-power level can be used by reducing frequency and maintaining the same impact energy per blow. Impact energies of approximately 50 ft. lb. are effective in the very hard formations.

Rotary-percussion action, which would give more efficient penetration, could easily be designed for with the lunar drill; however, whether the cutting action was percussion or rotary-percussion would depend on the type formations being drilled. It is doubtful if a design could be made which would hold the bit in contact with the harder formations with the low thrust available for the lunar drill.

IV. CHIP REMOVAL

Cuttings produced in drilling must be removed from the borehole in order to allow the drill to operate efficiently. These cuttings should be delivered to the surface in such a manner as to allow their systematic collection for chemical and physical analysis.

Normally, on earth, this is accomplished by flushing with a fluid, either liquid or gas. The fluid is usually pumped down the center of the drill stem and allowed to flow back to the surface in the annular space between the drill stem and the borehole wall. In certain cases, however, where excessive lost circulation is encountered, it has been found necessary to reverse this flow pattern. This has led to the development of vacuum drilling techniques where air is the flushing medium. These vacuum techniques are obviously dependent on the presence of a considerable amount of atmosphere which, of course, will not be the case on the moon.

Any fluid used to flush cuttings from the hole will undoubtedly penetrate the formation in the vicinity of the borehole to some extent. The higher the porosity and permeability of the formation, the greater will be the penetration. This will result in contamination of the subsurface formations by both the flushing fluid and some of the cuttings. What effect such contamination will have on the physical parameters to be measured by the downhole logging unit is a matter for serious thought and speculation.

Assuming that sufficient fluid can be carried to flush the hole in spite of the possibility of serious lost circulation, it is quite possible to have severe undercutting of the softer portions of the formation by the high velocity fluid stream. This can result in considerable uncertainty as to the utility of some of the downhole measurements (density and magnetic permeability, for example) which require that the variations in borehole diameter be maintained within certain fixed limits (-0.0", + 0.5").

Therefore, it appears highly desirable to clean the hole by purely mechanical means if at all possible.

An experimental drill rig was set up to determine if cuttings could effectively be removed from a hole by mechanical means. Fig. 7 shows this test rig, which consists of a tungsten carbide bit powered by an electric hammer. A separate electric motor is used to provide rotation for the purpose of carrying chips up the fluted bit.

The rate of penetration versus power for the electrical hammer used is shown in Fig. 11 and Fig. 12.

Fig. 8 shows the fluted 1-1/2" diameter drill after penetrating a block of Berea sandstone to the limit of the rig (10"). Fig. 13 is a plot of the rate of penetration versus depth for this hole. It is interesting to note that within the limits of the depth of hole drilled there did not appear to be a significant adverse effect on penetration rate caused by the mechanical cleaning.

Drilling by percussive action does not appear to generate excessive downhole waste heat. This is highly desirable if one is to consider the possibility of making equilibrium temperature determinations within the produced cavity.

V. LUNAR BIT DESIGN

Tungsten carbide inserts are commonly used in standard percussive driven rock bits and are capable of drilling the required depth hole in even the very hard rocks with quite acceptable wear. In addition, there does not appear to be any reason to expect adverse affects on this material by exposure to the lunar environment.

Although the complexity and uncertainty of core removal eliminate the possibility of using a core bit to produce the hole, it is not necessary to completely cut a full hole. The center of the hole is best handled by designing the bit so that a small central core is produced. This core is subsequently broken off in small pieces within the drill stem and discharged up the hole with the rest of the cuttings. See Fig. 9.

Spiral grooves or flutes are effective in mechanically cleaning the hole as evidenced by the previously mentioned experimental program.

The spiral flutes serve two functions. The first, of course, is to remove the cuttings from the immediate vicinity of the bit and to deliver them to an area within the spacecraft for analysis. The second, and not immediately obvious function of the flutes, is the prevention of a stuck drill caused by large particles sloughing off up the hole and becoming wedged between the bit and wall as the drill is being withdrawn.

VI. PRIME MOVERS

There appear to be three possible sources of energy worthy of consideration for powering a lunar drill. These are, (1) a monopropellant gas generator, (2) stored gas or liquid to be expanded, and (3) rechargeable batteries. Advantages and disadvantages of each system are listed below:

Monopropellant Gas Generator

Advantages

1) High energy per unit weight.
2) May be used to power drill directly as in conventional pneumatic hammer or to operate small turbine for high energy output with low hardware weight.
3) Exhaust available for pneumatic clearing of the hole.

Disadvantages

1) Inherent problems of valving and handling relatively high pressures and temperatures.
2) Stopping and restarting the gas generator, if necessary, requires a complex system.
3) Total available energy is fixed.

Stored Gas or Liquid to be Expanded

Advantages

1) High temperature not necessary.
2) Stopping and restarting is relatively easy.
3) Exhaust available for pneumatic cleaning of the hole.

Disadvantage

1) Very little total energy available.

Rechargeable Batteries

Advantages

1) Limit of the total energy available depends only upon the life of recharging machinery.

2) Stopping and starting as well as reversing of machinery is an extremely simple operation.

3) Very reliable off-the-shelf equipment is available.

Disadvantages

1) Unless subsequent development produces electric motors capable of operating with exposure to the lunar atmosphere, the motor must be sealed to control its environment.

In view of these considerations, it is felt that the lunar drill may best be powered by an electric motor operating in conjunction with rechargeable chemical batteries.

VII. CONCLUSIONS

1) Rotary drilling with the small thrust available is impractical over the range of hardness which must be anticipated for the lunar surface.

2) The addition of percussion action allows materials of the anticipated hardness to be penetrated at acceptable rates with reasonable rates of power consumption.

3) Mechanical cleaning of the hole appears to be entirely practical for holes of the depth and diameter anticipated when drilling under atmospheric condition. This must be evaluated under vacuum conditions before any final flight design can be set.

4) Reliability and versatility required of the prime movers for the drill are best satisfied by using electric motors. This choice allows operation over a much greater period of time since rechargeable batteries can be used as a source of power.

5) A tungsten carbide tipped bit similar to a conventional rock bit, as shown in Fig. 10, appears to be entirely satisfactory for the lunar drill. Note that the bit produces a small central core which is broken off within the drill stem and discharged up the hole with the rest of the cuttings.

VIII. RECOMMENDATIONS

Based on an experimental program and literature investigation, it is felt that the lunar drill requirements may best be satisfied by a machine which produces a hole by a percussive action. The cuttings should be removed from this hole by mechanical means. A spiral fluted shaft rotated at 100 RPM has satisfactorily performed this mechanical chip removal during the drilling under atmospheric conditions of holes up to 1-1/2" in diameter and 10" deep in Berea sandstone. The drill should be electrically powered.

A preliminary design for the lunar drill has been prepared. See Fig. 14. The estimated weight of this drill is 35 lbs. and its rate of power consumption is 375 watts. When drilling in Berea sandstone, this machine will produce a 1.25" diameter hole at a rate

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of 0.50" per minute.

The most important undetermined quantity remaining is an experimental evaluation of the behavior of aggregates of small particles (cuttings) under high vacuum conditions. It has been postulated that the absence of adsorbed surface layers of air or water molecules will radically alter the behavior of dust. These adsorbed molecules appear to act as a lubricant for the dust particles. Whether or not these effects are significant for the larger particle sizes present in the drill cuttings is vital to the evaluation of the mechanical cleaning of the borehole under lunar atmospheric conditions.

It is our recommendation that a vacuum experimental drilling program (not necessarily for full depth hole) be undertaken as the next step in the development of the lunar drill.

APPENDIX "A"

Experimental Evaluation of Low Thrust Rotary Drilling as Applied to Lunar Exploration.

I. APPARATUS

A standard drill press was the basis for the experimental evaluation of rotary drilling. This machine was modified as follows:

1) The motor drive unit was replaced by an electrically driven Graham variable speed transmission, thus allowing continuous speed selection from 0 to 550 RPM. A tachometer was mounted on the upper end of the drill shaft so that rotational speed could be accurately known.

2) Spring loading of the drill feed pinion was removed. A larger pulley was mounted on one end of this pinion shaft. One end of a cable was secured to the periphery of this pulley. The free end of this cable was secured to a small platform to which known weight could be added. The pulley was sized so that a 5 lb. weight on the platform produced 50 lbs. force of thrust at the drill bit. By measuring the vertical travel of the weight carrying platform, bit travel could be accurately determined.

3) The rock sample to be drilled was supported on a table which was free to rotate about a vertical axis coaxial with the drill. By measuring the torque required to prevent rotation of the work during drilling, the torque exerted by the drill was determined. The rate of power dissipation at the bit was then

determined by means of the formula;

$$W = \frac{2 \pi nT}{33000}$$

where,

W = rate of power dissipation, horse power

n = revolutions per minute of drill

T = torque on drill table, (lbs. force)(ft.).

With these modifications, drilling rates as a function of thrust, RPM, torque, and diameter of hole drilled could be determined for a pure rotary system. Maximum depth of hole possible with this apparatus was 4".

II. STANDARDS

It was decided to conduct preliminary testing of all drills in a medium hardness sandstone - Berea. This choice was based primarily on convenience. In addition, this sandstone appeared to be a reasonable compromise between the soft Purmice and the very hard Gabbro which represent extreme estimates of the lunar surface. This sandstone, however, was found to be extremely abrasive, and produced very rapid wear on the rotary bits employed.

III. DRILL BITS

The following bits were examined in the course of the drilling program:

1) Conventional rotary masonry bit. These were single bladed drag bits. Tungsten carbide insert in a conventional fluted metal drill. 1/4" to 1" diameter.

2) Two "clusterite" tipped drag bit configurations supplied by Reed-Roller Bit. These bits were fluted for mechanical cleaning of the hole. 1-1/2" diameter (Fig. 4).

3) Two and three bladed drag bits; the blades being made up from cutting surface of diamond core bits. These were prepared in our shop. 1-1/4" diameter (Fig. 5).

4) Two forms of air or liquid cooled and flushed diamond drag bits supplied by Hycalog, Inc. 1-1/2" diameter.

5) Three custom built diamond-studded three-bladed drag bits prepared by Hycalog, Inc. Fluted stem for mechanical cleaning of hole. Provision for use of air or water to flush and/or cool the bit. 1" diameter (Fig. 6).

IV. TESTING PROCEDURE

Tests were set up to evaluate drilling rates in sandstone as functions of thrust and rotational speed of the bit. The three thrust values used were 20, 50, and 70 lbs. Rotational speeds were 100, 200, and 300 RPM. For comparison, Austin limestone (very soft) and Gabbro (very hard) were tested at 50 lbs. thrust and 200 RPM. Running time for each drilling rate evaluated was 30 minutes, or a drill penetration of 1", whichever occurred first.

V. EXPERIMENTAL RESULTS

These may be summarized very briefly. For diameters of 1" or greater, none of the drills would penetrate Berea sandstone with 50 lbs. thrust. In most cases, the thrust had to be increased to at least 200 lbs. before any appreciable rate of penetration was achieved.

APPENDIX "B"

Experimental Evaluation of Mechanical Chip Clearance Using Low Thrust Percussive Drilling.

A Black and Decker electric hammer (Model 104) was used to provide percussion to a tungsten carbide bit. The bit was rotated by a separate electric motor to provide mechanical cleaning action by means of a set of spiral grooves cut in the drill rod (Fig. 9).

In order to determine the capabilities of the electric hammer, tests were made in both Berea sandstone and Harris granite. The results are shown in Fig. 11 and Fig. 12. These tests were conducted by varying the voltage to the motor driving the hammer. The power consumed was then measured by means of a watt meter. This method of varying power was used primarily because of its simplicity. It has the disadvantage in this case of changing both the energy delivered per blow and the frequency. After it was determined that this piece of equipment could satisfactorily produce 1" diameter short depth hole with the proper force, it was mounted in the test rig shown in Fig. 7.

A special design bit was fabricated in order to drill a relatively deep hole. This bit was essentially a standard rock bit with the tungsten carbide inserts reground and the center removed. The inserts were ground so that the leading edge was vertical and the face of the bit was relieved 15°. This left a cutting point at an angle of 75°. A 1/32" horizontal flat was then ground on the cutting edge to prevent breakage due to impact. Only slight wear was noticeable on the face of this bit after a total of 40" had been drilled in the Berea stone.

The deep hole tests were conducted as follows:

1) Power to the electric hammer was set at 800 watts.

2) Rotary power input was measured as a function of depth and the difference in no load power consumed and power consumed at full depth was taken as the power required to rotate the bit under 10" of cuttings. This is actually a somewhat conservative approach, since the gear box loss increases with an increase in load. However, the rotational power required to keep the bit rotating at 100 RPM was only 20 watts at the full depth of 10". Since the power was this low it is felt that no further effort to refine the number is justified at this time.

3) Static force on the bit was regulated by a system of counter-balances. This was necessary since the machinery, as it was set up, weighed more than the available thrust for the lunar drill.

4) Penetration was measured by a scale and indicator attached to the test stand. For the sake of simplicity the entire drive mechanism was mounted on a slide assembly which moved down with the drill.

5) Percussion was added at a frequency of 2,200 cycles/min.

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TABLE I

ROTARY DRILLING DATA

Bit Description	Material Drilled	Loading Force (lb)	Rate of Penetration (in/min)	Power Consumed (watts)	RPM	Wear
Carbide masonry drill, 1" dia.	Berea sandstone	180	.5	250	450	Excessive
Carbide masonry drill, 1/2" dia.	Berea sandstone	57	2.1	45.5	350	Excessive
Carbide masonry drill, 1/4" dia.	Berea sandstone	57	3.05	10.2	250	Good
Clusterite tipped bit, 1-7/16" dia. Design (A)	Berea sandstone	57	.025	37.5	100	Excessive
Clusterite tipped bit, 1-7/16" dia. Design (B)	Berea sandstone	57	.065	37.5	100	Excessive
Steel burr 3/4" dia.	Berea sandstone	57	.025	12.0	200	Excessive
Diamond bit, 1-1/4" dia. Design (A)	Berea sandstone	57	.11	9.5	200	Moderate
Diamond bit, 1-1/4" dia. Design (B)	Berea sandstone	57	.025	14.0	200	Moderate
Diamond bit, 1" dia. Special Design	Berea sandstone	57	-No measured penetration-			
	Gabbro	57	-No measured penetration-			
	Pumicite	26	2.9	>50	100	Good
	Austin Lime	26	.58	>50	100	Good

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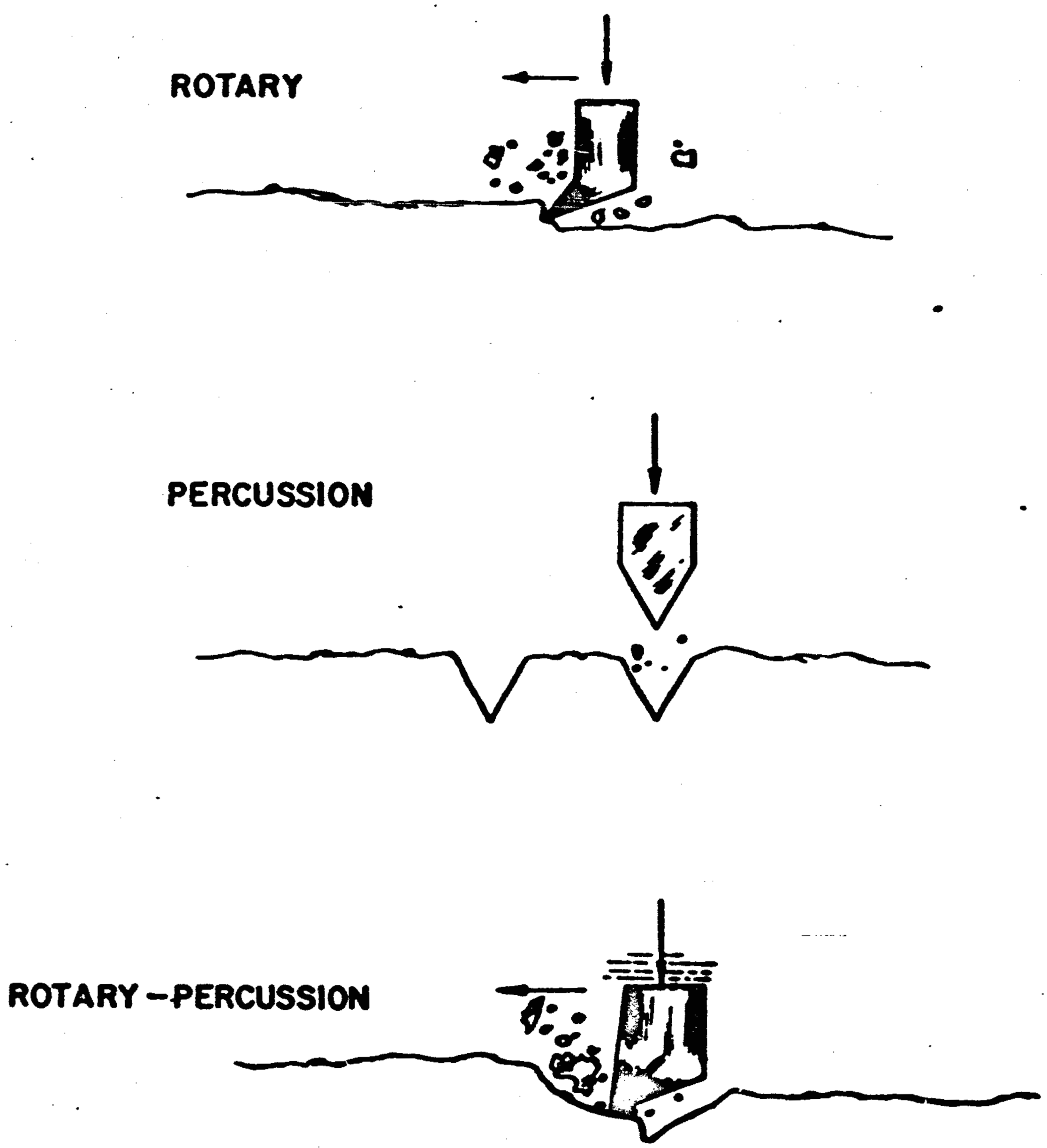

FIGURE 1

ELEMENTS OF MECHANICAL DRILLING

PENETRATION RATE VS APPLIED THRUST FOR VARIOUS METHODS OF MECHANICAL DRILLING

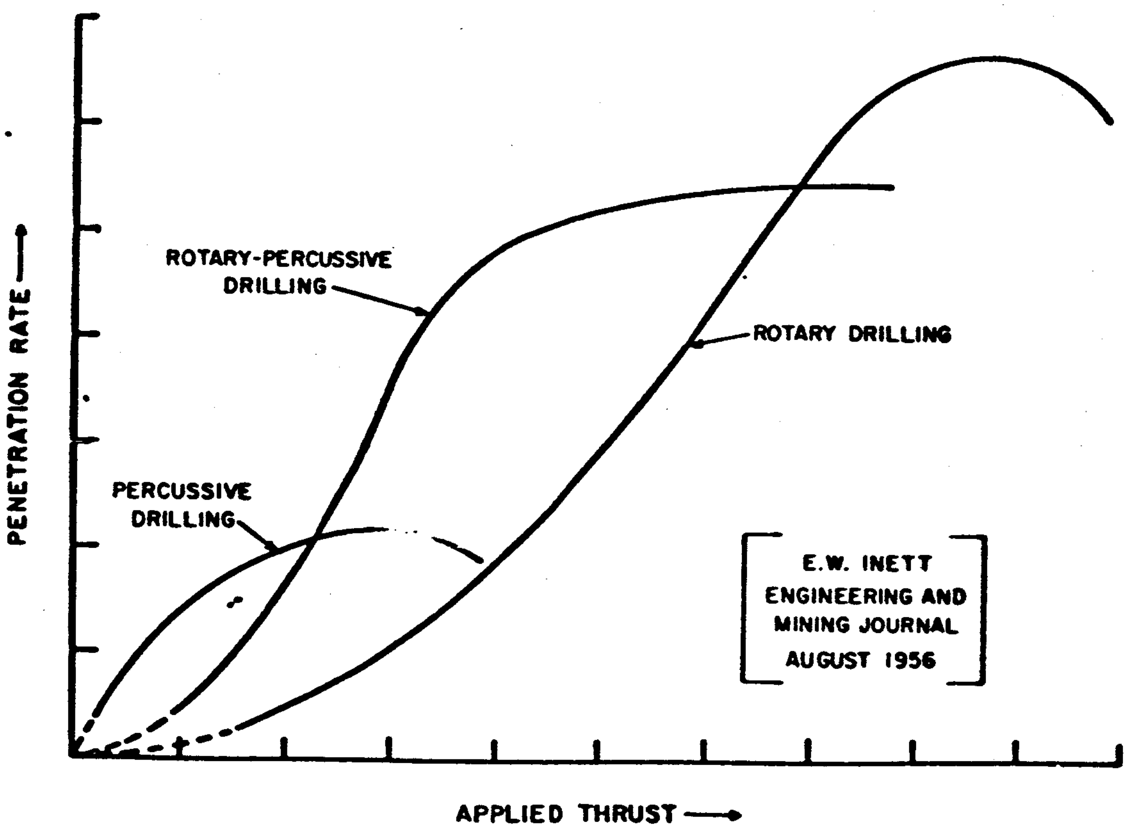

FIGURE 2

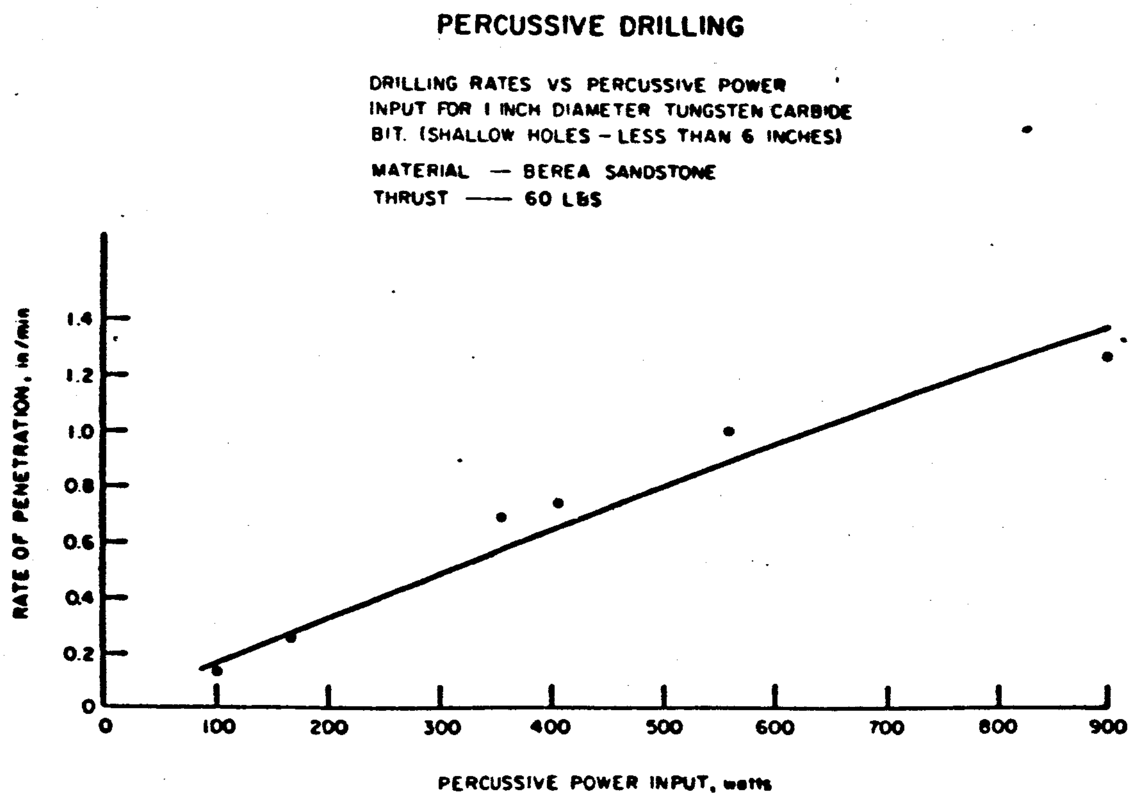
PERCUSSIVE DRILLING
DRILLING RATES VS PERCUSSIVE POWER INPUT FOR 1 INCH DIAMETER TUNGSTEN CARBIDE BIT. (SHALLOW HOLES - LESS THAN 6 INCHES)
MATERIAL — BEREA SANDSTONE
THRUST —— 60 LBS
RATE OF PENETRATION, in/min
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
800
900
PERCUSSIVE POWER INPUT, watts

FIGURE 11

PERCUSSIVE DRILLING

DRILLING RATES VS PERCUSSIVE POWER INPUT FOR 1 INCH DIAMETER TUNGSTEN CARBIDE BIT. (SHALLOW HOLES - LESS THAN 6 INCHES)

MATERIAL — HARRIS GRANITE

THRUST —— 60 LBS

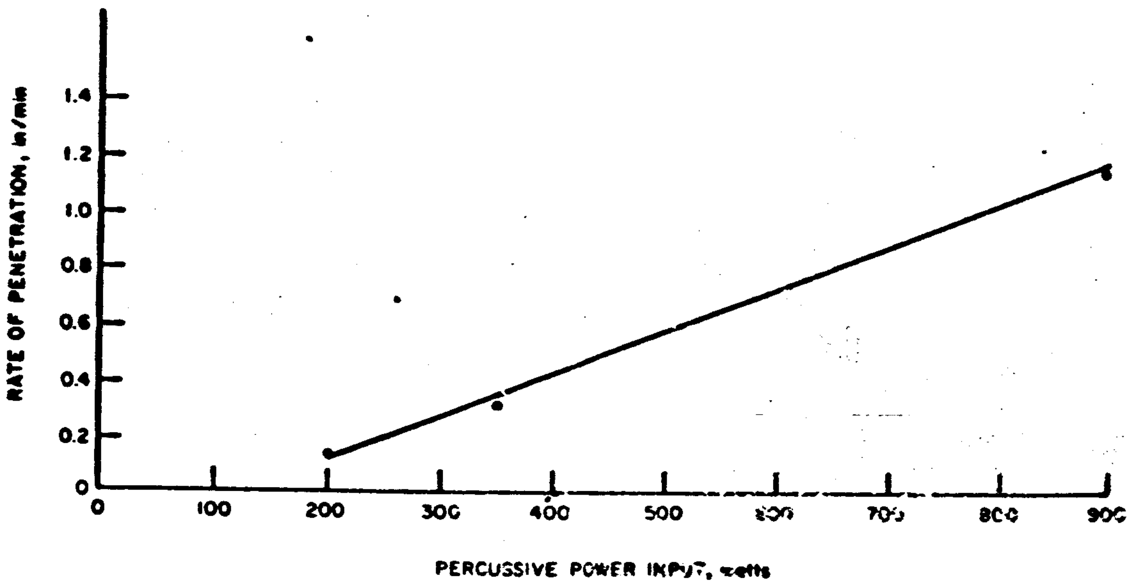

FIGURE 12

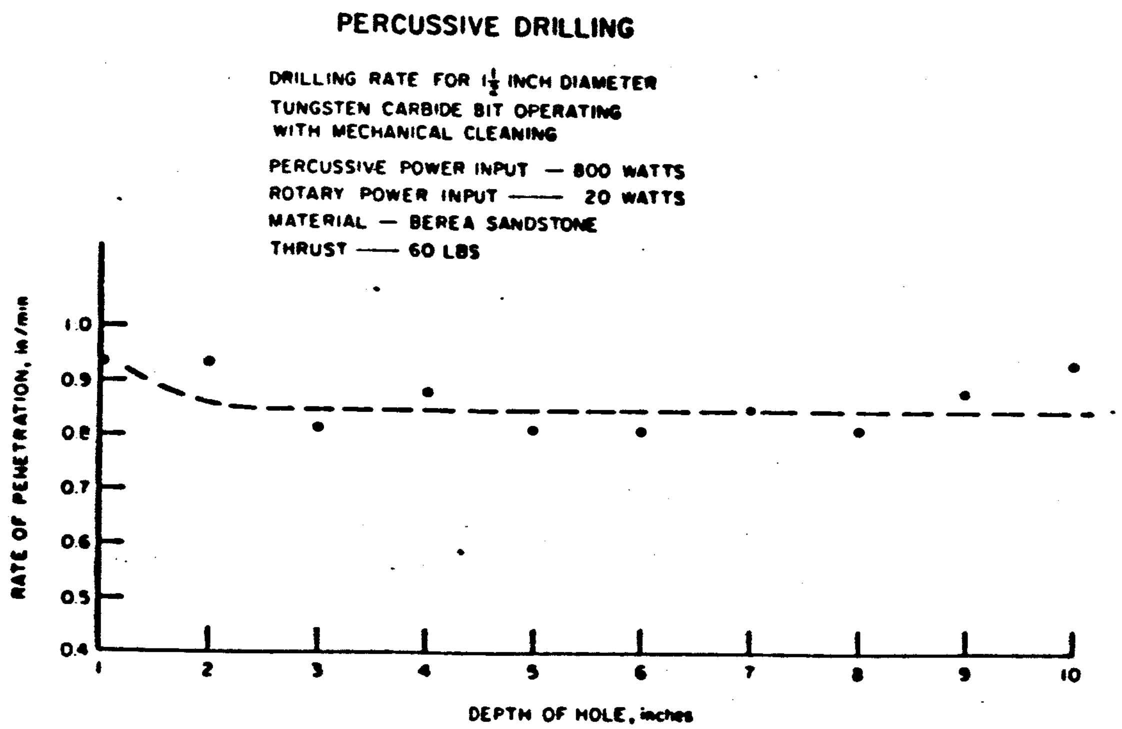

FIGURE 13

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ENVELOPE LENGTH	6 Ft.
ENVELOPE DIAMETER	6 In.
WEIGHT	35 Lb.
POWER CONSUMPTION	375 Watts
RATE OF PENETRATION	1/2 In./Min. - BEREA SANDSTONE
HOLE DIAMETER	1-1/4 In.

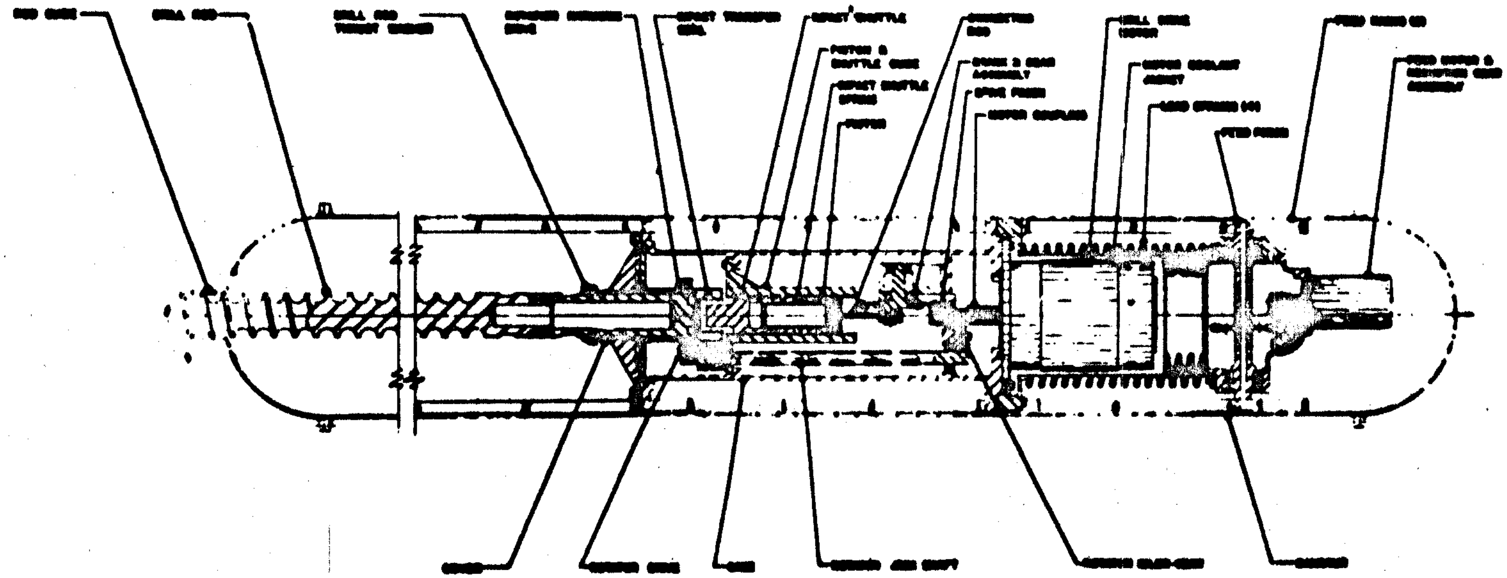

FIGURE 14

PROPOSED LUNAR DRILL

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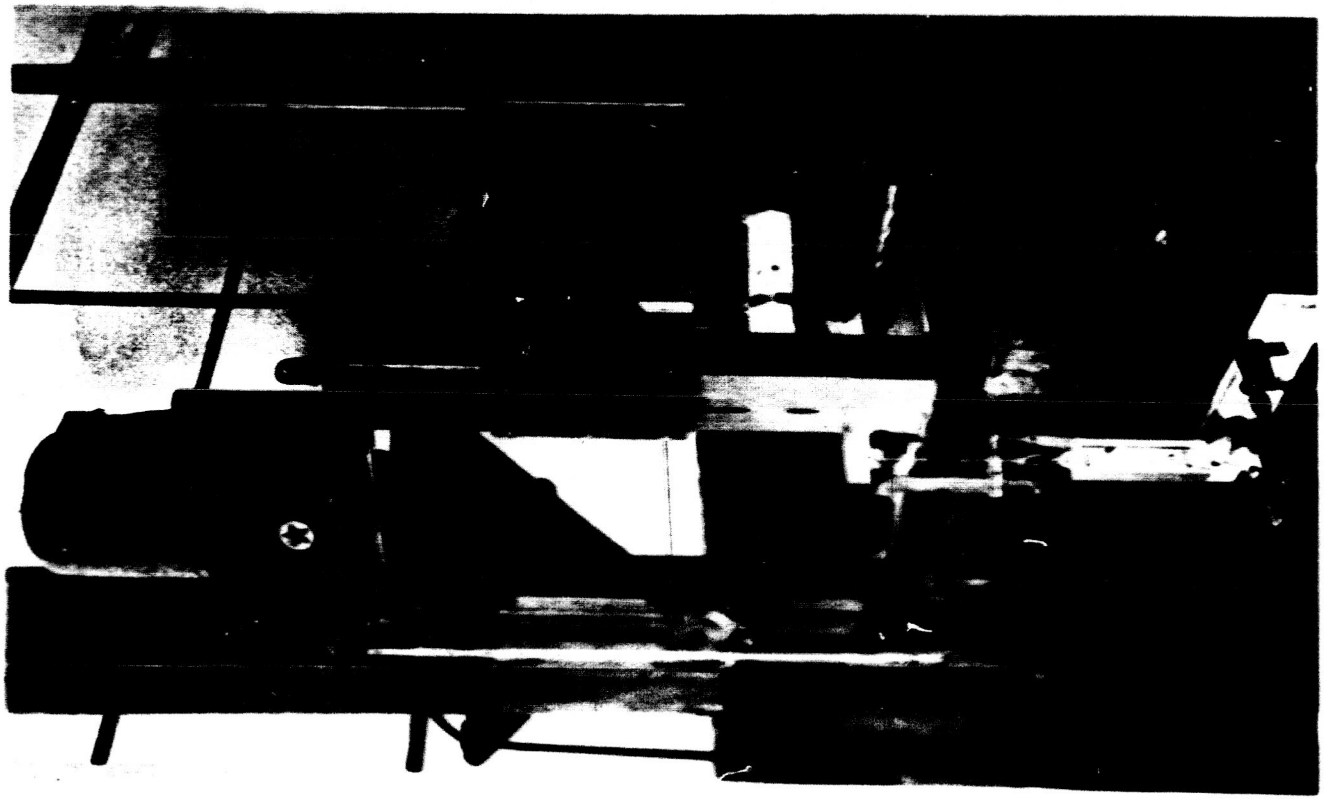


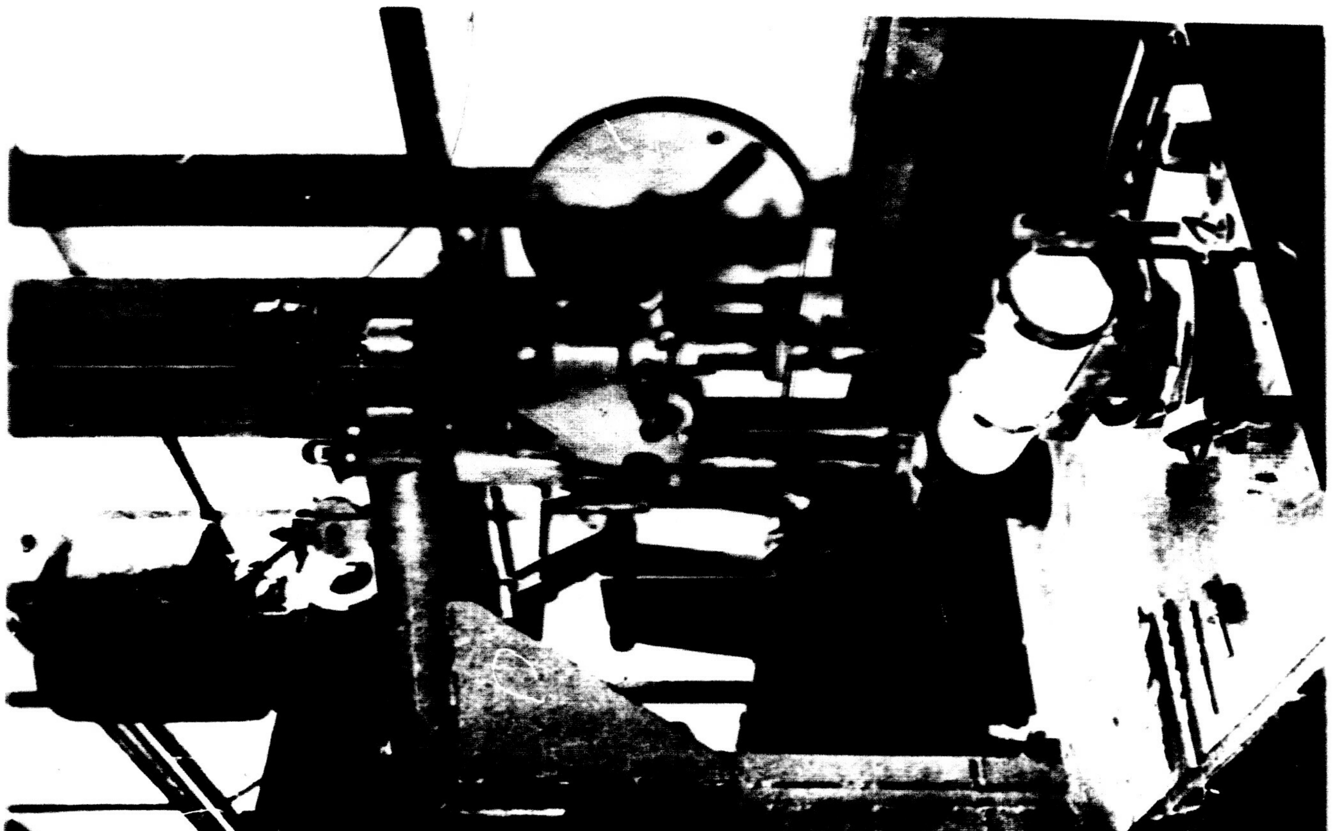


FIGURE [illegible]

TEST APPARATUS FOR ROTARY DRILLING

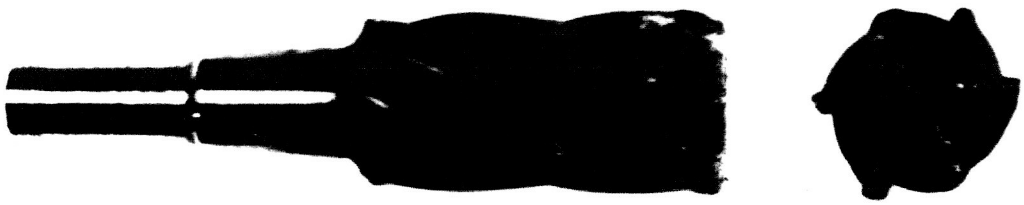
DESIGN A

DESIGN B

FIGURE 4

CLUSTERITE TIPPED BITS 1-7/16" DIAMETER

DESIGN A



DESIGN B

FIGURE 5

DIAMOND BITS 1-1/4" DIAMETER

FIGURE 6

DIAMOND BIT 1" DIAMETER SPECIAL DESIGN

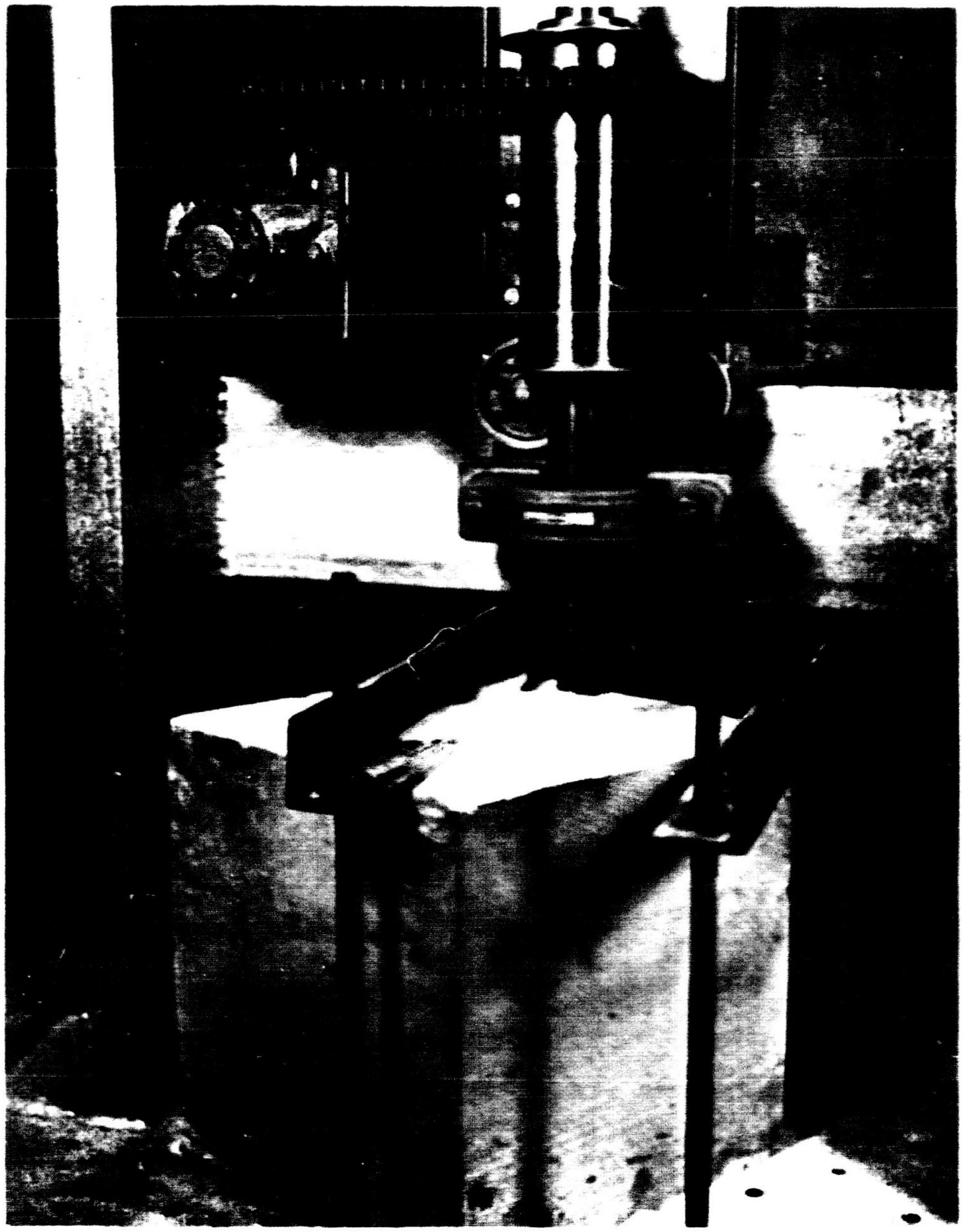


FIGURE 8

BERKA SANDSTONE DRILLED WITHOUT FLUID
TO FULL DEPTH OF TEST APPARATUS

FIGURE 7

TEST APPARATUS FOR DRY DRILLING WITH PERCUSSION

1:794 21

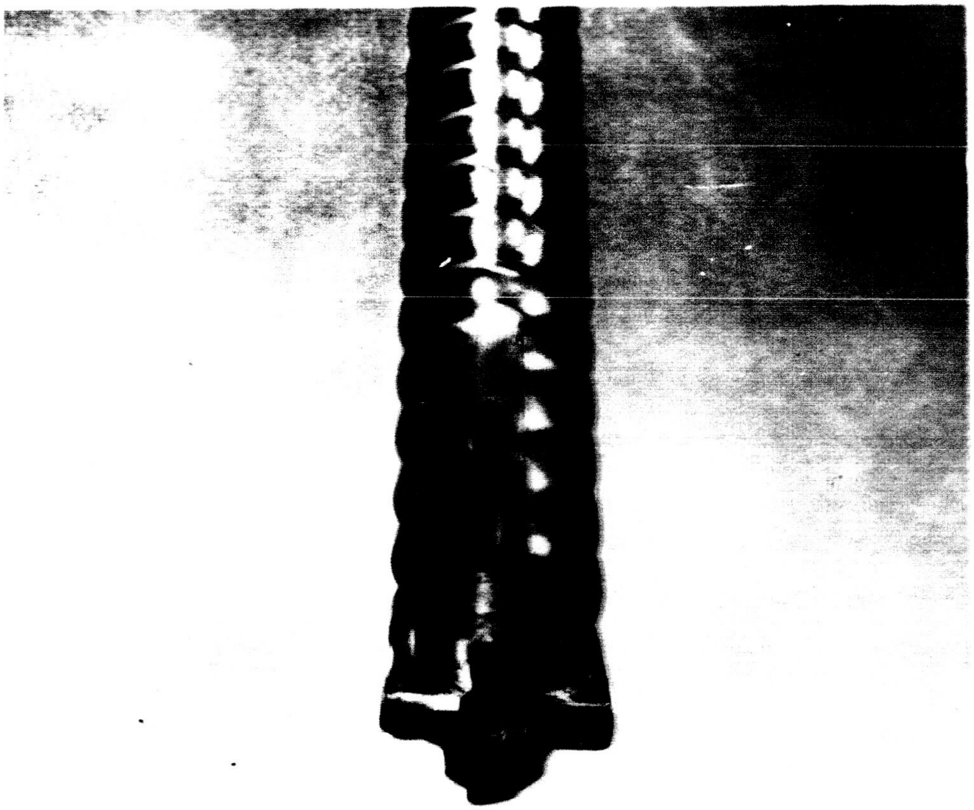


FIGURE 9

1-1/2" DIAMETER BIT FOR PERCUSSIVE DRILLING
AND MECHANICAL CLEANING

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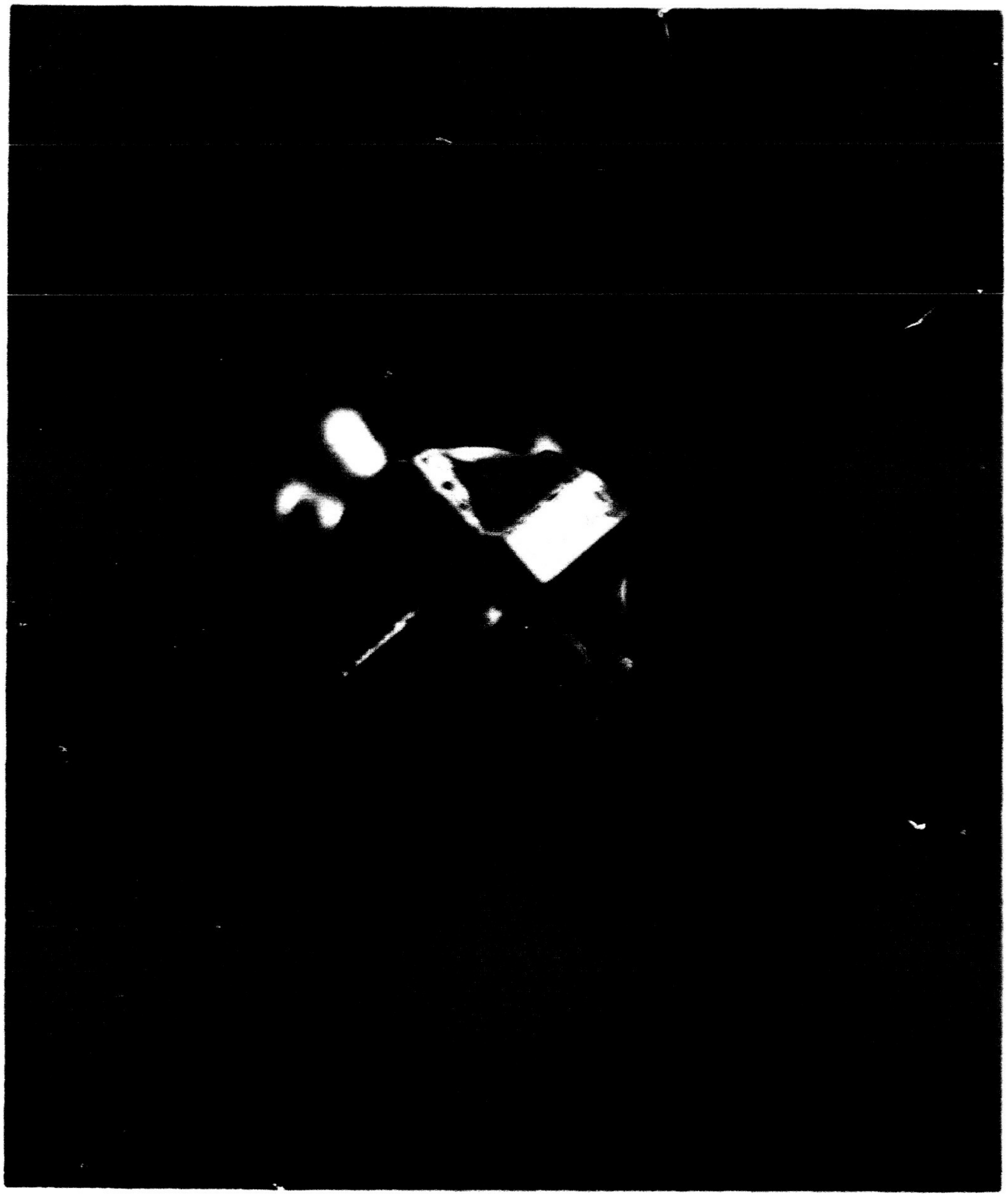

FIGURE 10

END VIEW OF PERCUSSIVE BIT SHOWING OPENING
FOR REMOVAL OF CENTER

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